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TECHNICAL REPORT

Radiation Protection in the Application of Active Detection Technologies

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July 2013

HDTRA1-09-C-0040

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14. ABSTRACT
Commentary from the National Council on Radiation Protection and Measurements (NCRP) Scientific Committee 1-18. NCRP was asked to provide a general review of Active Detection Technology (ADT) and their anticipated uses, to analyze their potential for exposure to humans, and to provide guidelines to ensure that doses to operating personnel and bystanders are within recommended limits. NCRP was further asked to provide recommendations on how to best achieve the recommended guidelines for dose limits.

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Conversion Factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY ⟶ BY ⟶ TO GET
TO GET ⟵ BY ⟵ DIVIDE

angstrom	1.000 000 x E -10	meters (m)
atmosphere (normal)	1.013 25 x E +2	kilo pascal (kPa)
bar	1.000 000 x E +2	kilo pascal (kPa)
barn	1.000 000 x E -28	$meter^2$ (m^2)
British thermal unit (thermochemical)	1.054 350 x E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical/cm^2)	4.184 000 x E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 x E +1	*giga bacquerel (GBq)
degree (angle)	1.745 329 x E -2	radian (rad)
degree Fahrenheit	$t_k = (t^{\circ}f + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 x E -19	joule (J)
erg	1.000 000 x E -7	joule (J)
erg/second	1.000 000 x E -7	watt (W)
foot	3.048 000 x E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 x E -3	$meter^3$ (m^3)
inch	2.540 000 x E -2	meter (m)
jerk	1.000 000 x E +9	joule (J)
joule/kilogram (J/kg) radiation dose absorbed	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 x E +3	newton (N)
kip/$inch^2$ (ksi)	6.894 757 x E +3	kilo pascal (kPa)
ktap	1.000 000 x E +2	newton-second/m^2 ($N\text{-}s/m^2$)
micron	1.000 000 x E -6	meter (m)
mil	2.540 000 x E -5	meter (m)
mile (international)	1.609 344 x E +3	meter (m)
ounce	2.834 952 x E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 x E -1	newton-meter (N-m)
pound-force/inch	1.751 268 x E +2	newton/meter (N/m)
pound-force/$foot^2$	4.788 026 x E -2	kilo pascal (kPa)
pound-force/$inch^2$ (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 x E -1	kilogram (kg)
pound-mass-$foot^2$ (moment of inertia)	4.214 011 x E -2	kilogram-$meter^2$ ($kg\text{-}m^2$)
pound-mass/$foot^3$	1.601 846 x E +1	kilogram-$meter^3$ (kg/m^3)
rad (radiation dose absorbed)	1.000 000 x E -2	**Gray (Gy)
roentgen	2.579 760 x E -4	coulomb/kilogram (C/kg)
shake	1.000 000 x E -8	second (s)
slug	1.459 390 x E +1	kilogram (kg)
torr (mm Hg, 0^0 C)	1.333 22 x E -1	kilo pascal (kPa)

*The bacquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.

**The Gray (GY) is the SI unit of absorbed radiation.

Preface

The United States faces continued threats of attack from terrorist organizations and their supporters. These threats include the possible use of biological, chemical, radiological, and nuclear sources capable of causing harm and death to many individuals. Radioactive material used to contaminate or irradiate has the potential to cause great disruption and panic, threatening health and safety. Conventional explosives coupled to radioactive materials can appreciably increase dispersal, further increasing the concerns about health, safety and disruption of normal routines. Stolen or improvised nuclear explosive devices have the potential for widespread and long-lasting damage to human health and the built and natural environment. The use of fissile materials in nuclear devices could cause severe injury or death and widespread disruption of the sense of well-being and the essential components of life such as food, water, utilities, transportation modes and other basic services.

The U.S. government has a compelling need to locate, deactivate, and impound or destroy these nuclear materials before they can be used for terrorism. Appropriate agencies require technologies, devices, and techniques that will allow them to detect these materials and devices before they are brought into the United States and/or deployed. Detection systems must be sensitive enough to detect materials even when small in quantity or heavily shielded. Some devices must be mobile to access specific sites. To this end, the Defense Threat Reduction Agency (DTRA) of the U.S. Department of Defense is sponsoring research to develop Active Detection Technology (ADT) devices that can achieve the above criteria. While passive detection systems are usually capable of detecting radioactive materials with naturally high activity, the radiation emitted from fissile materials is often low enough (energy and/or intensity) to preclude detection. The purpose of ADT systems is to stimulate this material to emit detectable, radiation signatures. ADT is a broad term for devices that generate radiation in order to stimulate a physical response from nuclear materials, allowing identification of those materials from a distance.

To obtain radiation protection guidance on appropriate use of these devices, DTRA contracted with the National Council on Radiation Protection and Measurements (NCRP). NCRP was asked to review the ADTs and their anticipated uses, to analyze their potential for exposure to humans, and to provide guidelines to ensure that doses to operating personnel and bystanders are within recommended limits. NCRP was further asked to provide recommendations on how to best achieve the recommended guidelines for dose limits.

To facilitate accomplishment of the above charge, NCRP convened two Scientific Committees, Scientific Committee 1-18 and Scientific Committee 1-19. Scientific Committee 1-18 was tasked with addressing the application of fundamental principles of radiation protection to ADT systems and developing recommendations for radiation protection goals and philosophy for such systems. Scientific Committee 1-19 was asked to consider the technical aspects of ADTs and to make recommendations addressing the requirements necessary for safe use as recommended by Scientific Committee 1-18. Each Scientific Committee was charged with putting their findings into the form of a Commentary. This Commentary was prepared by Scientific Committee 1-18. Serving on the Committee were:

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Thomas S. Tenforde
President

1. Introduction

With the threat of terrorism, concerns about the use of radiological and nuclear weapons are high. Billions of dollars have been appropriated in the United States for the development and deployment of new technologies for monitoring nuclear weapons and materials within the United States and overseas (Medalia, 2009). The U.S. Congress has enacted laws requiring that containers be scanned by imaging and radiation detection equipment before loading onto vessels in foreign ports (9/11 Commission Act, 2007), with the intention of preventing terrorists from smuggling nuclear weapons or fissile materials [special nuclear material (SNM)] into the country.

Nuclear detection can impede a terrorist nuclear attack in two ways: deterrence and defense. A successful detection capability, in combination with the inherent difficulties of constructing an effective nuclear weapon, could convince adversaries that any attempt to launch a nuclear attack will fail or that such an attack would be too complex to execute. These consequences could dissuade them from action. If, however, deterrence fails, detection systems would be needed, allowing the discovery of materials and interdiction to prevent their use. The detection technologies could be used to search vehicles, structures, containers, and possibly individuals for SNM or weapons at border crossings, transit routes, and other locations of concern.

The United States Government is actively pursuing efforts to develop, acquire, and support the deployment of enhanced detection systems for nuclear and radiological materials. While the Domestic Nuclear Detection Office (DNDO) in the Department of Homeland Security (DHS) is the lead agency in this area, both the Department of Energy (DOE) and the Defense Threat Reduction Agency (DTRA) in the Department of Defense (DoD) support programs to develop and field an Active Detection Technology (ADT) system. This Commentary focuses on the efforts of DTRA to deploy a detection system that addresses their military mission. It is intended as guidance to inform the development process with respect to radiation protection issues. The comments and recommendations of this report are broadly applicable to all active detection technologies for fissile material. Subsequent reports are planned that will delve into greater technological details regarding implementation of the guidelines laid out here.

This Commentary reviews the new remote detection technologies that are being developed, focusing on the requirements for radiation protection of people and the environment and provides guidelines to ensure that doses are within recommended limits for operating personnel and bystanders[1] in the inspected areas. Section 1 puts the requirement for the new technologies into context and provides an overview of security screening and contraband detection systems that have previously been reviewed by NCRP. Section 2 describes the basic characteristics of the possible active detection technologies. Section 3 reviews radiation effects and considers dose limits for ADT systems. Section 4 discusses radiation protection requirements as they relate to ADTs. Section 5 focuses on the ethical considerations and communication requirements associated with ADT usage. And, finally, Section 6 presents a summary of the key points and recommendations for the future.

The dose limits recommended in this Commentary are in keeping with the limits previously recommended by NCRP (2003a; 2004; 2007) and ICRP (2007) for occupational and public exposure from any source, including security screening applications, contraband detection and the use of ADT systems.

1.1 Defense Threat Reduction Agency's Development Efforts

The Defense Threat Reduction Agency (DTRA) oversees the development of new radiological and nuclear detection technologies in support of the U.S. Department of Defense (DoD) mission of detecting, identifying, and eliminating threats from radiological and nuclear weapons of mass destruction worldwide (DTRA, 2008). In this context, the devices would not be used for routine screening, but rather for targeted interrogations based on credible information. For national defense, DoD might need to search for nuclear materials in hostile environments with equipment that can withstand a range of harsh conditions. With international cooperation, ADTs may be used in international waters or on foreign soil. These requirements distinguish the

[1] For consistency throughout this Commentary, the term "personnel" is used to indicate those who are involved with the operation of the ADT systems and "bystanders" are workers involved with the shipping or handling of suspicious containers or members of the general public who are in the area but ignorant of any SNM and unaware that they might be at risk of radiation exposure. Those who are clearly identified as knowingly transporting SNM are "terrorists" as referred to in Chapter 113B: 2332b and 2339 of Title 18, United States Code and not addressed in this report.

DoD technologies from those that might be deployed for homeland defense at border crossings (Medalia, 2009).

DTRA's program has the goal of standoff detection[2] of radiological and fissile materials. ADT systems are one of the promising candidate technologies capable of accomplishing this goal. These systems use radiation to stimulate detectable signatures from fissile materials. The possible radiation types include high-intensity bremsstrahlung radiation, monoenergetic gamma-ray sources, and particulate radiations including neutrons, protons and muons. The resulting signatures include prompt and delayed neutron and gamma emissions from induced fission events, x rays from muon interactions with high-Z materials, and other signatures resulting from particulate or electromagnetic radiation interactions with SNM and other potential radiological weapons materials. The stimulated signatures would facilitate long-range detection of the fissile materials using detectors that are spatially and temporally linked to the active detection sources.

Recently DTRA issued a Broad Agency Announcement that called for development of new standoff detection technologies (DTRA, 2008). This Broad Agency Announcement set forth the requirement that there be a minimum of 100 m standoff between the interrogating device (and operators) and the targeted object. In addition, it required a minimum distance of 50 m from object to the detector that need not be co-located with the interrogating device. The expectation was that the equipment would be operable outdoors from sea level to 1,500 m elevation under a broad range of humidity and temperatures. Other possible environmental conditions include the inherent motion of the platform, such as a ship at sea, and sea spray.

While the technologies to meet these demanding specifications are being developed, DTRA asked NCRP to provide guidance on the effective design, development and deployment of the proposed ADTs with a focus on the radiological safety and health and environmental protection aspects of these systems. While some risk is associated with radiation generating devices such as ADTs, the intention is to design and use the system in a way that would ensure that risks are as low as reasonably achievable and potential radiation doses do not exceed acceptable limits for operating personnel and bystanders.

[2] Standoff detection involves sensing the presence of radioactive materials when the interrogating and monitoring devices are physically separated from the targeted object.

1.2 The Need for Active Detection Technology Systems

Active Detection Technology (ADT) systems use a beam of radiation to interrogate an object or location suspected of containing nuclear materials. If nuclear materials are present, such interrogation will stimulate the release of signature radiation that, ideally, will allow identification of type, quantity, and location of the nuclear materials. At a minimum, an ADT system will include an interrogation source, one or more receptors to detect stimulated radiation, and software to interpret the detected signal. There are a range of candidate interrogation radiations, including high-energy photons, protons, neutrons and muons. Likewise, there is a range of associated risks to operating personnel, to individuals who might be exposed to the interrogation beam, and to individuals who may be exposed to the stimulated response.

Inspection of cargo containers represent one application of ADTs. Lubenau and Strom (2002) estimated the number of cargo containers imported into the United States to be approximately 50,000 per day (Figure 1.1). While it is impossible to manually inspect each container and its individual contents, rapid, accurate scanning devices can accomplish such a task. ADT systems might fill this need.

Fig. 1.1. Seaport terminal example showing cargo conveyance ship, cranes, and lay-down yard (Kouzes, 2005). At least 50,000 cargo containers have been estimated to come into the United States daily.

Another potential application of ADT systems is detection at long distances (Figure 1.2). Distant detection of nuclear materials is advantageous when looking for nuclear materials along smuggling routes, in distant vehicles or aboard ships at sea, and in facilities, in an inaccessible territory or in a city (Medalia, 2009). These operations might require scanning of large areas to locate materials or rapid data acquisition if the materials are moving quickly across a detection field.

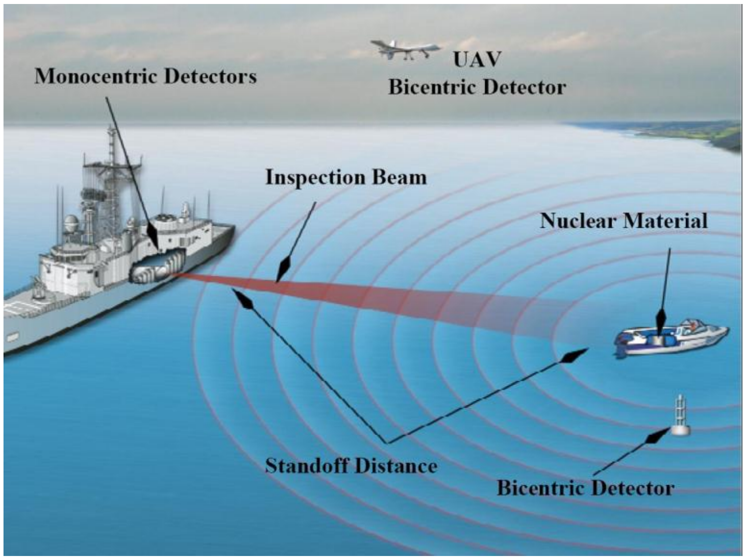

Fig. 1.2. Detection of special nuclear material at distance of up to hundreds of meters presents unusual problems. UAV: unmanned aerial vehicle. Monocentric Detectors: detector co-localized with interrogating device. Bicentric Detector: detector remote from interrogating device.

Nuclear weapons, which can be small (~1 m in length), require fissile material, typically the uranium isotope-235 (^{235}U) or the plutonium isotope-239 (^{239}Pu). However, the energies of the gamma rays emitted by both are low, making detection and identification difficult, especially if this material is shielded by a high atomic-numbered (Z) material such as lead. In addition, detection requires that the detectors be relatively close to the material, usually within a few meters to no more than a few tens of meters. DTRA considers the development of effective detection systems high priority since technologies with long standoff distances are not yet available. Systems have been developed that take advantage of the fluorescence that occurs when high energy photons interact with the electrons of uranium or plutonium. Electrons under these conditions are either elevated to a higher energy state or ejected from the atom. Either case generates photons with energies that are highly characteristic of the element emitting them. Existing computerized detection systems can readily differentiate the specific energies of the secondary photons being emitted from the material during the fluorescence process. The use of higher energy photons can also be employed to take advantage of the preferred scattering angles for photons interacting with specific materials. Detectors at angles from the source-to-object path can measure the scattering at the specific angles. Still higher energy photons can lead to gamma-neutron (γ-n) interactions with uranium or plutonium, which result in the emission of photons from the excited nucleus that have higher energy than those emitted with normal ^{235}U or ^{239}Pu radioactive decay. Passive and active neutron detection systems have also been used in safeguards applications for decades. ADT systems in development and under consideration (Section 2) will take advantage of these concepts.

1.3 Existing Technologies

NCRP, in the past, looked at emerging technologies for homeland security applications and developed guidelines for their usage (NCRP, 2003a; 2003b; 2007). Selected systems are described here to provide a general overview of the technology.

1.3.1 Screening Devices for Screening Humans

NCRP Commentary No. 16 (2003b) addressed radiation devices for human screening, their use, and their exposure potentials. Primarily the two types of screening systems evaluated were the x-ray backscatter devices (Figure 1.3) and the x-ray transmission devices (Figure 1.4). These devices produce x-ray energies similar to those used in clinical diagnostic imaging [i.e., using tube voltages of 50 to 125 kilovolt-peak (kVp)]. The backscatter devices work well for detecting objects on the outside of the body but are unable to image objects inside the body, such as items swallowed or inserted into a body cavity. Individuals imaged by these devices are usually exposed to less than 0.25 μSv per scan. Consequently, it would require an improbable number of scans (1000 or more) per year to a single individual for that individual to receive an annual effective dose that exceeds the recommended administrative control of 0.25 mSv y^{-1} to a member of the general public from a single source (25 % of the 1 mSv y^{-1} limit) (NCRP, 1993). Many of these scanners were installed in airports in the wake of the December 25, 2009 terrorist attempt to set off a chemical explosive on a Detroit-bound airplane (Capehart, 2010).

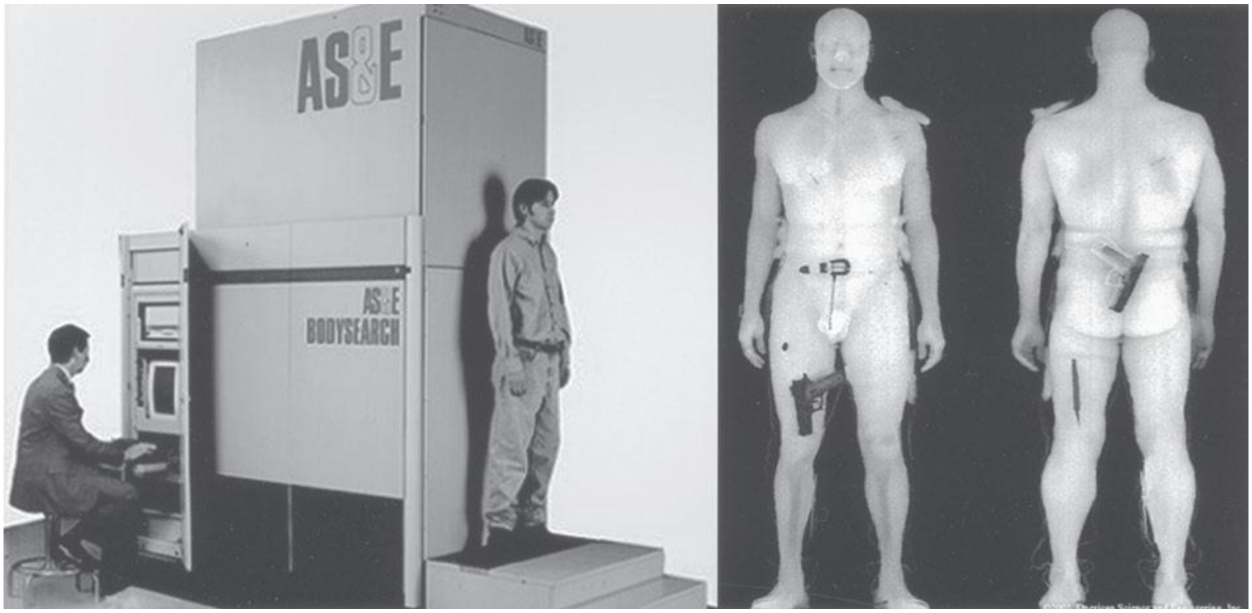

Fig. 1.3 American Science and Engineering's BodySearchTM backscatter system and sample images (photographs courtesy of American Science and Engineering, Inc., Billerica, Massachusetts).

Transmission scanning devices (Figure 1.4) usually expose the individual to higher doses than backscatter devices. Individuals are exposed to effective doses up to 10 μSv per scan, indicating that these devices should be used cautiously and the number of individuals or the number of scans per individual should be limited (i.e., they are limited-use technologies).

1.3.2 Pulsed Fast Neutron Analysis Systems for Security Surveillance

Pulsed fast neutron analysis (PFNA) systems for the detection of weapons or other contraband materials held in large containers such as truck trailers were evaluated by the DoD and its contractors several years ago. The system that was designed involved nanosecond pulses of 8.5 MeV neutrons for scanning cargo contents. Detection of prompt gamma emissions that result when fast neutrons are absorbed [the (n, γ) reaction] by the contents of the containers provides data for construction of a three-dimensional image of the elemental composition of the contents of the container. The PFNA beam was designed to have a sufficiently high fluence (about 6.5×10^5 neutrons cm^{-2}) for imaging and determining the chemical signature of the cargo content, even with partial shielding of the cargo content.

Fig. 1.4 The Conpass transmission system and sample image (photographs courtesy of X-RayEquipment Company, Miami, Florida).

NCRP Commentary No. 17 (2003a) evaluated several aspects of health and environmental safety of a full-scale PFNA system operating at a border crossing into the United States. The considerations included measurement technology suitable for evaluating dose to inadvertently exposed individuals and other materials that may be present in a scanned cargo container; the potential upper limit of dose received by exposed individuals in a scanned container; and the activation products that would be created in scanned materials over a wide range of atomic numbers, including pharmaceutical products and medical devices. NCRP also reviewed the radiation safety plan for routine operation of a PFNA scanning system that was prepared as part of the required environmental assessment. Overall, it was concluded that the dose to an inadvertently exposed individual could generally be maintained within the annual public effective dose limit of 1 mSv for frequent lifetime exposures, with the highest potential effective dose at or below 5 mSv, which is acceptable for infrequent exposures. The levels of activation products, including those in food, pharmaceutical products, and medical devices were determined to be very low and within recommended limits.

A prototype PFNA system for operational testing was deployed at a border crossing in El Paso, Texas. The system was found to be generally reliable, and measurements of potential radiation doses to inadvertently exposed individuals were made with the use of anthropomorphic physical phantoms contained within typical cargo contents and configurations. It was later decided, however, that the cost of producing a large number of PFNA security surveillance systems would be unacceptably high and the program was discontinued.

1.3.3 Cargo Scanners Using Accelerator-Produced High-Energy X Rays

NCRP Commentary 20 (2007) evaluated the use of high-energy x rays produced by accelerators and used in cargo scanning. The images produced by Cargo Advanced Automated Radiography Systems (CAARS) are similar to the images produced by the security screening systems used with humans [i.e., either backscatter images (Figure 1.5) or transmission images]. NCRP Commentary 20 recommends that:

- The effective dose to an individual inadvertently exposed to radiation within a conveyance that is being inspected in the CAARS exclusion zone not exceed 5 mSv.
- The accelerator energy, beam current, filter configuration and minimum scan speed be controlled and the CAARS system be interlocked so that irradiation is terminated, if necessary to prevent the effective dose to the occupant of a conveyance from exceeding 5 mSv.
- The CAARS staff receive training on the health hazards of radiation and on the effect of shielding, distance, and time in reducing radiation levels.
- That CAARS facility staff wear appropriate dosimeters to verify that the effective dose to staff outside the exclusion zone is consistent with the design specification of not exceeding 0.5 μSv in an hour.
- The effective dose at the perimeter of a CAARS facility (i.e., the area unrestricted to members of the public) should not exceed an administrative control of 0.25 mSv y^{-1}.
- A quality assurance-quality control system should be established that includes periodic testing and documentation to ensure that systems continue to perform within design specifications throughout their useful operating lifetime.

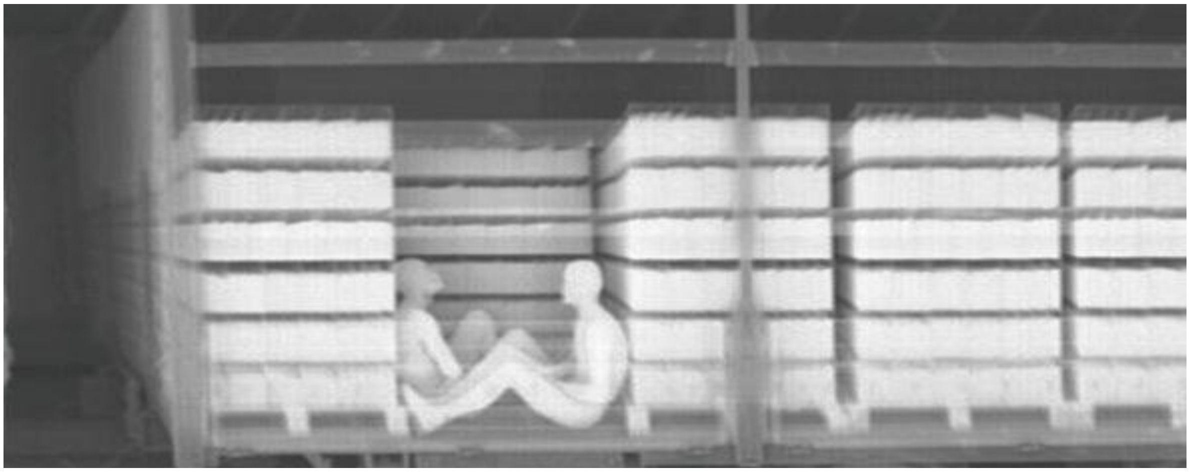

Fig. 1.5. Backscatter image of inadvertently-exposed individuals in a cargo conveyance (courtesy of American Science and Engineering, Inc., Billerica, Massachusetts).

1.3.4 Gamma Radiation for Contraband Detection

High-energy gamma radiation sources can also be used to obtain non-intrusive imaging of the contents of closed moving vehicles (Figure 1.6), cargo containers or cargo on pallets. The vehicle or cargo is exposed to gamma rays from a radioactive source, usually ^{60}Co or ^{137}Cs. On the opposite side of the inspected object, sodium iodide (NaI) detectors measure the transmitted radiation and software generates a density map or image that can be viewed by the operator. The distance between source and detectors is limited; in most configurations it is less than 30 m. These devices have been used successfully at borders for cargo truck and railroad freight-car inspections. They have detected weapons, hazardous material (including chemical and radioactive sources), drugs, stolen vehicles and other illegal cargo, stowaways, illegal immigrants and other undeclared cargo. The devices are only sensitive to density differences and cannot specifically identify SNM.

Fig. 1.6. A gamma-ray scanner system for use with transportation vehicles (SAIC, 2009).

The growing use and applications of gamma-ray screening systems requires consideration of the same radiation protection principles and practices discussed in Sections 3 and 4 of this Commentary. Unintentional exposures of the operator, public or the environment in the direct beam would be the greatest concern of these devices. The manufacturer recommends additional barriers external to the device be established to reduce the likelihood of exposure. However, the radiation output of these devices is generally low. For example, the units made by Science Applications International Corporation (SAIC, 2008) generate a nominal dose per scan of 0.04 μSv for the ^{137}Cs source configuration, and 0.1 μSv for the ^{60}Co source at the centerline of a targeted object.

2. Radiation Technologies for Active Detection Technology Systems

2.1 Detection Technologies

There are two general types of remote detection technologies available for illicit nuclear materials – passive and active. Passive technologies use detectors that are sensitive to the emissions from the source. Passive detection of explosives, for instance, uses sensitive detectors (e.g., ion mobility spectroscopy, chemoluminescence, or other means) to recognize one or more component chemicals. Passive technologies do not require direct interaction with the source. For detection of contraband nuclear materials, the capabilities of passive technologies can be severely limited by shielding, type of radiation emission, and distance. Because SNM generates only weak radioactive emissions, passive nuclear detectors can pick up these emissions from no more than a few meters away and only in the absence of substantial shielding.

ADTs have the potential to overcome many of the difficulties associated with passive detection. ADTs generate radiation of sufficient energy to stimulate a characteristic energy emission from nuclear materials, which may allow identification of the materials from a distance. Shielding designed to reduce the normally low-energy radiation from the radioactive decay of the nuclear materials may be penetrated by the ADT radiation to reveal the presence of hidden materials.

In the design of ADTs, the detectors can either be co-located with the interrogation source or they can be on separate platforms. The latter option might permit detection from distributed sensors, from ships or trucks, or unmanned aerial or underwater vehicles. At the time this Commentary is published, the specific technology or technologies to be used for ADT systems remains undetermined. This Commentary considers several of the most plausible ADT systems, focusing on the source of ADT radiation. This Commentary considers only accelerator-based radiation sources. Proton accelerators and electron accelerators are likely the best sources of such secondary radiations (photons, muons, neutrons) with sufficient energy and flux density to accomplish the goals of ADT systems.

2.2 Radiation Interrogation Sources

The purpose of this Section is to provide an overall summary of the various types of ionizing radiation that might be used in ADT systems.

2.2.1 Electrons

High-speed electrons lose some of their kinetic energy in material through the production of bremsstrahlung (photon) radiation. The energy of the photon produced can range anywhere from near zero to the maximum energy of the electrons. For the thick targets that are likely to be used for ADTs, the number of bremsstrahlung photons as a function of photon energy E per unit energy decreases with energy proportional to E^{-2} (IAEA, 1979). For high kinetic energy electrons, in the tens of MeV range, the resulting photon energy is predominantly on the order of 50 % or less of the kinetic energy of the electron. The atomic number of the target material with which the electrons interact impacts the intensity of the photons produced. Thus, the choice of the energy to which the electron is accelerated and the atomic number of the target material determine the energy spectrum and the intensity of the generated bremsstrahlung photons. The technology for electron accelerators is well-established as these devices have had a long history of use in research and are the predominant sources for electron beams and high-energy photon beams for treating cancer patients.

. In order to limit the spread of bremsstrahlung photon energies and to achieve optimum interaction and detection efficiency, “filtering”, such as is standard practice with x-ray technology, can be used. This can also help to minimize the dose delivered to both operating personnel and bystanders during a particular ADT application.

The use of electron accelerators to generate bremsstrahlung radiation is the most mature of the ADT systems in development (Medalia, 2009). With the current technology, relatively compact electron accelerators can be built with energies of several tens of MeV, average current on the order of 100 μA and with different pulse lengths and repetition rates. The electron beam is aimed at a high-Z target that generates bremsstrahlung photons with a range of energies up to the energy of the electron beam. Long distances in air attenuate lower-energy photons in the beam, so the targeted object must be exposed to higher energy x rays. The associated detectors might be located in the same unit as the accelerator especially if the unit is operating in a pulsed mode.

2.2.2 Protons

Accelerated protons can be used to generate the radiations needed to perform the interrogations intrinsic to ADT systems. While accelerated protons cannot compete with accelerated electrons as a viable and prodigious source of photons, protons are the most effective accelerated particle for producing neutrons, both prompt and delayed (Section 2.2.4), and muons (Section 2.2.3) for ADT systems.

When protons interact with high Z material, they produce electromagnetic cascades or emissions of detectable photons. Proton beams interacting with SNM can cause fission by way of either direct action of the protons on the nucleus or through neutron-nucleus interactions from neutrons released when the protons interact with the SNM or shielding material.

Radiation fields associated with proton accelerators are unique and generally require considerably more shielding to protect operating and maintenance personnel and bystanders. Proton accelerators are generally much larger than electron accelerators. In general, proton acceleration systems are an order of magnitude more complex and more expensive than electron/photon systems.

2.2.3 Muons

Muons are much heavier versions of electrons. A muon can have either positive or negative electronic charge and a mass that is about 200 times the mass of the electron. Due to this larger mass, muons do not decelerate sharply in electromagnetic fields (such as those close to the nucleus of atoms) or produce as much bremsstrahlung radiation as electrons. This makes muons much more penetrating than electrons.

Muon production requires an accelerator of considerable energy and size. Although electron beams with energies well above the production threshold of 211 MeV can generate muons, the most effective way of producing muons is by using protons. This method involves aiming a high-energy proton beam (>>140 MeV) into a target material to produce subatomic particles called pions. The pions produced by the protons in a muon production mode are allowed to traverse a region of vacuum (preferred) or air where they very quickly decay (in ~ 10^{-8} s) into muons (within distances of a few meters). Since the pions participate in the strong (i.e., nuclear) interaction, a backstop absorbs the pions and allows penetration by the muons. Muons formed when pions decay continue traveling in the same direction as the pions. Muons have relatively long ionization ranges making them likely to be exploited by ADTs, principally to produce muonic atoms in high-Z materials. In practice, to produce a useful muon beam, the acceleration of a high intensity beam of protons to a kinetic energy of about 1 GeV or more is required.

A plausible additional application of muons in ADT systems is the emission of muonic x rays by muons in atomic quantum states. Such x rays would give a unique energy signature of high-Z materials in this particular active interrogation scheme. To do this would require the energy of the interrogating muons to be adjusted appropriately to stop, primarily by ionization, in the material of interest.

2.2.4 Neutrons

Neutrons also represent a potential interrogation radiation source for use with ADT systems. Although there are radioactive neutron sources that couple alpha-emitting radionuclides, such as ^{210}Po, ^{239}Pu or ^{241}Am with a neutron-generating material such as beryllium (Be) or deuterium oxide (D_2O) that readily emit neutrons from an (α, n) reaction, it is unlikely that such sources would provide the quantity of neutrons needed for interrogation at the specified distances for ADT systems. Electron accelerators that generate photons at energies above 10 MeV can be used to produce neutron beams; however, the most efficient accelerated particle for producing neutron beams is the proton. Proton accelerators are more likely to produce neutrons in sufficient quantities to be useful at ADT system interrogation distances. Unlike the other particles discussed in this section, neutrons cannot be collimated with an electric field due to their lack of charge. Because of the isotropic emission of generated neutrons, a major challenge with these systems is collimation.

2.3 Hazard Considerations

Accelerators have the potential to produce very high instantaneous, pulse, and average dose rates, which could present significant risks for anyone exposed. Thus, care must be exercised in the development and use of such devices to minimize the risks and ensure that operating personnel and bystanders do not receive radiation doses that exceed the dose limits recommended in this Commentary (Section 3). In particular, it will be important to prevent individuals from receiving direct exposure to the beam between the device and the inspected area. Approaches for limiting the risks are discussed further in Section 4.2.

Another concern is the possibility that a sufficient fluence of neutrons, either produced as an unwanted byproduct of irradiation or deliberately produced for imaging or detection purposes, might result in the detonation of a surreptitiously concealed nuclear weapon. Verification that this is not possible should be made during development and prior to the use of ADT systems.

The use of accelerators also includes the use of additional hazardous substances or devices such as electrical hazards, cryogenic systems, vacuum systems, laser aiming systems, chemical hazards, etc., and induced radioactivity within the accelerator housing. While the consideration of these potential hazards is beyond the scope of this Commentary, they must be considered in the development of the safety programs for the use of ADT systems.

3. Radiation Effects, As Low As Reasonably Achievable, and Recommended Dose Limits

3.1 Radiation Effects

Radiation-induced health effects fall into two general categories: deterministic and stochastic. Deterministic effects occur only after relatively large doses of radiation (on the order of 1 Gy and higher). Examples of deterministic effects include neutropenia [the loss of certain white blood cells that help to fight infection] and skin erythema (reddening and possible blistering). Both white blood cells depression and skin effects become more severe with increased radiation dose. Stochastic effects, which include endpoints such as cancer and genetic aberrations, are effects in which the probability of occurrence, but not the severity of the disease, increases with absorbed dose. The induction of stochastic effects is considered to be the principal effect resulting from exposure to low doses of ionizing radiation (NCRP, 1993). Susceptibility to both deterministic and stochastic effects depends on individual characteristics such as age, gender and genetic disposition. The health effects of radiation are described in greater detail in Appendices A and B.

3.2 Radiation Protection Guidelines

Radiation protection aims (1) to prevent the occurrence of clinically significant radiation-induced deterministic effects by adhering to dose limits that are below the apparent threshold levels, and (2) to limit the risk of stochastic effects (i.e., cancer and genetic effects) to a reasonable level in relation to societal needs, values, benefits gained, and economic factors (NCRP, 1993). Previous studies (IAEA, 2006; ICRP, 1991; 2007; NCRP, 1993; 2003a; 2004; 2007) have presented guidelines for achieving these objectives and recommended dose limits for both workers and the general public.

Radiation exposure at any selected dose limit may have some associated level of risk. For this reason, NCRP (1993) recommends the following three guidelines of radiation protection:

1. The need to justify any activity that involves radiation exposure on the basis that the expected benefits to society exceed the overall societal cost (i.e., justification).

2. The need to ensure that the total societal detriment from such justifiable activities or practices is maintained as low as is reasonably achievable, economic and social factors being taken into account [i.e., the as low as (is) reasonably achievable (ALARA) principle].

3. The need to apply individual dose limits to ensure that the procedures of justification and ALARA do not result in individuals or groups of individuals exceeding levels of acceptable risk (i.e., dose limitation) (Section 3.3).

The first principle, justification, refers to the broad societal decision that is formally or informally made and based on the conclusion that the expected benefits to society exceed the overall societal cost. NCRP and radiation protection specialists can provide estimates of radiation levels and accompanying radiation risks that are integral to making a societal decision, but cannot render an opinion of the net benefit or cost based on these radiation aspects alone. Societal benefits should exceed the risks. In the case of ADTs, an analysis of the societal benefits is likely to include a reduction in the threat of a nuclear detonation, a cataclysmic event generally acknowledged to be worthy of extraordinary preventive measures. In situations where potential benefit and confidence that the system would produce meaningful information are very high, exposing individuals to risk might be justified (Section 5.1.1). If, on the other hand, the system were to have very low sensitivity or it was to be used to interrogate containers with low likelihood of containing SNM, benefit would be less evident and justification would be more difficult.

The ALARA principle was introduced into radiation safety programs to reduce doses and potential deleterious effects of radiation to the extent practicable. While any exposure may have the potential to cause an effect, the probability is reduced as the dose decreases. The principle of ALARA takes into consideration "social and economic factors" in determining acceptable levels. It is not simply a requirement for dose reductions irrespective of the dose level; sound judgment is essential for its proper application. A level of radiation protection that is ALARA implies neither maximum protection nor maximum resource expenditure, but rather that potentially detrimental effects and resource expenditures have been optimized to yield the greatest net benefit.

3.3 Dose Limits

Occupationally-exposed individuals and members of the public have different dose limits, which reflect the doses received from all controllable sources combined, excluding medical exposures and natural background. Because those who are occupationally exposed make their livelihoods by voluntarily working with radiation, they realize benefits of employment in association with their radiation exposure. A worker's acceptance of heightened risk is related to his specific role and that person can be trained on the precautions to take to limit dose.

In contrast, the dose to members of the public may be received involuntarily. For this reason and others, use of lower dose limits for members of the public than for workers has been widely accepted as sound regulatory policy throughout the world (IAEA, 1996; ICRP, 2007; NCRP, 1993, 2007). However, these radiation exposures to members of the public may provide significant indirect benefits such as increased safety and security in travel as a result of baggage screening with x-ray systems.

3.3.1 Occupational Exposure

For occupational exposure of radiation workers, NCRP (1993) recommends that the cumulative lifetime effective dose not exceed the age of the individual in years times 10 mSv, with an annual limit of 50 mSv effective dose. This system of dose limitation constrains the excess lifetime risk of fatal cancer to less than 3 % for the maximally exposed individual, which is comparable to the lifetime fatal accident risk in safe industry.

For declared pregnant women in occupational conditions, NCRP (1993) recommends a limit on the equivalent dose to the embryo/fetus of no more than 0.5 mSv in a month. This monthly limit was developed to sufficiently protect the embryo or fetus from harmful radiation effects.

3.3.2 Exposure to Members of the Public

NCRP (1993) recommends an annual effective dose limit of 1 mSv for continuous or frequent exposures to members of the public. However, on an infrequent basis, the effective dose to a member of the public may exceed 1 mSv, up to a maximum of 5 mSv in a year. These limits exclude exposures from natural background radiation and radiation exposure associated with medical diagnosis and treatment. Exposures to the annual radiation limits over the course of 75 years correspond to an excess lifetime risk of fatal cancers of about 0.4% (see Appendix B).

The 1 mSv limit on annual effective dose was based on several considerations including the risks associated with a given dose and their uncertainties, annual doses to the public from exposure to natural background excluding radon, the potential for exposure over an entire lifetime, and the wide range of sensitivities to radiation in the general population (NCRP, 1993). This recommendation is intended to limit exposure of members of the public to levels of risk that are comparable to risks from other common sources (NCRP, 1993). A maximum annual effective dose limit of 5 mSv is recommended for infrequent annual exposures because an annual effective dose in excess of the 1 mSv recommendation, usually to a small group of people, need not be regarded as especially hazardous, provided this dose does not occur often to the same groups and that the exposure to individuals in these groups does not exceed an average annual effective dose of about 1 mSv.

Because a member of the public might be exposed to more than one source of radiation in a year, NCRP (1993) recommended that: "…whenever the potential exists for exposure of an individual member of the public to exceed 25 % of the annual effective dose limit as a result of irradiation attributable to a single site, the site operator should ensure that the annual exposure of the maximally exposed individual, from all man-made exposures (excepting that individual's medical exposure), does not exceed 1 mSv on a continuous basis. Alternatively, if such an assessment is not conducted, no single source or set of sources under one control should result in an individual being exposed to more than 0.25 mSv annually."

3.3.3 Sensitive Groups

Certain subgroups [e.g., children, the developing embryo or fetus, genetically susceptible individuals, such as individuals who are heterozygous for the ataxia telangiectasia gene (Hall and Angele, 1999; ICRP, 1998), or individuals with chronic diseases such as hepatitis or smokers (NA/NRC, 2006)] exhibit higher risk from radiation exposures. NCRP recommends special consideration for individuals or groups that are significantly more sensitive for risk from radiation exposure. For example, as noted in Section 3.3.1, NCRP (1993) recommends limiting the equivalent dose to the embryo or fetus of an occupationally-exposed declared pregnant woman to 0.5 mSv per month. While NCRP does not specifically address the embryo or fetus in its recommendations for members of the public, the recommended maximum of 0.25 mSv effective dose per year for security screening of members of the public (NCRP, 2003b) is considerably lower than the constraints for the fetus of occupationally exposed pregnant women.

3.4 Dose Limits for Active Detection Technologies

In developing these recommendations, NCRP recognizes that the proposed ADT systems differ in significant respects from the security systems considered in prior NCRP Commentaries, raising unusual and challenging issues for the application of the principles of radiation protection.

The ADT systems under consideration are intended only for a specific and high priority national security application—standoff detection and interdiction of nuclear weapons of mass destruction devices, and special nuclear materials (SNM) that could be used in such devices. The general-use systems considered in NCRP Commentary No. 16 (2003b) are focused on routine screening of humans, an application for which the low exposure levels involved (maximum of 0.1 μSv per scan for General-Use Systems and 10 μSv per scan for Limited-Use Systems) have been deemed acceptable. The cargo screening devices considered in NCRP Commentaries No. 17 and No. 20 (2003a; 2007) are intended to detect a wide range of potential threats or contraband materials including but not limited to the national security-related nuclear materials addressed in this Commentary. As a result, they may be applied in some circumstances to achieve routine law enforcement objectives (e.g., the detection of smuggled drugs or conventional weapons), which may require different justification analyses than are involved with the unique national security objectives of ADT systems. The cargo screening systems considered in earlier NCRP commentaries are deployed in fixed facilities with tightly controlled access to the irradiated area (Figure 3.1), so that the only possibility for inadvertent exposure would involve individuals in the truck cab or hiding in cargo containers who did not or could not heed the warnings that would be given prior to irradiation.

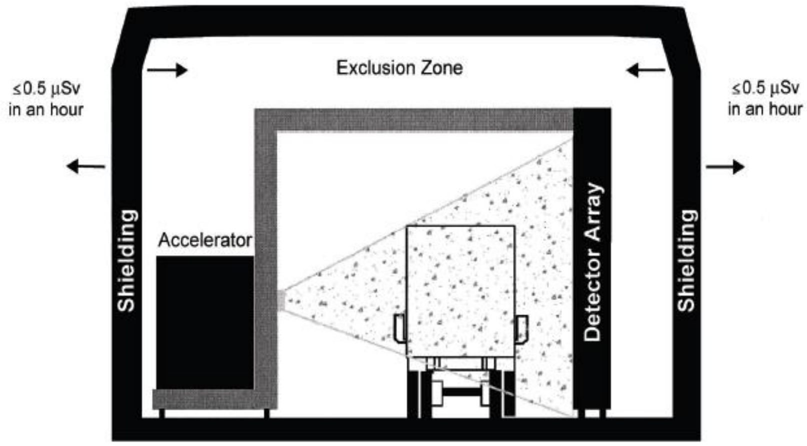

Fig. 3.1. Schematic representation of a Cargo Advanced Automated Radiography System (CAARS) design. No individual is permitted in the exclusion zone when a conveyance is being scanned. The cumulative effective dose rate in the area outside the exclusion zone will not exceed 0.5 µSv in an hour.

Unlike the human and cargo screening systems considered in earlier commentaries, the full range of operational capabilities of the proposed ADT systems are still in development at this time. While the minimal radiation levels required to obtain operationally useful information about the presence or absence of nuclear materials at the distances being contemplated for ADT systems is understood, many factors influence the operationally effective radiation dose (and the associated potential for exposures to members of the public). Information about the radiation levels required to obtain useful information from an interrogation will be needed for the appropriate application of the principles of justification and ALARA. (NCRP recognizes that some possible scenarios involve the potential use of ADT systems under conditions of imminent and grave threats to national security, or under uniquely military environments. Such situations for prevention of catastrophic consequences may be considered emergency situations in which normal public limits on radiation dose do not apply but strong justification and optimization of protective strategies are emphasized [see ICRP, 2007]).

Because ADT systems are intended for inspection of objects at a substantially greater distance and in much less controlled environments than the other systems considered previously by NCRP, an exclusion zone (as shown in Figure 3.1), where access is physically limited, may not be possible. Furthermore, because of the greater distances between the radiation source and the object, the radiation levels near the source could be much higher than those of other systems. Individuals who might stray into the area close to the ADT system are likely to receive substantially higher doses than those recommended for the general public and possibly even greater than the recommended occupational exposure limits. Operational procedures will need to be developed to prevent such exposures [e.g., through use of systems to detect intruders and terminate the beam if necessary (Section 4)].

NCRP recommends that the effective dose to any bystander not exceed 5 mSv per inspection event from an ADT system. This dose limit should apply to the total dose an individual might receive during an inspection event, taking into consideration the possibility that a bystander might receive multiple exposures as a result of repeated scanning of a targeted object during the event.

The individuals involved with the transportation and operation of ADT systems or with the collection of information about a targeted object will have adequate radiation safety training specific to the use of the ADT system and assigned occupational exposure limits as determined by their employers.

This dose limit is consistent with NCRP's recognition that exceptions to the 1 mSv y^{-1} public dose limit for prolonged or repeated exposures might be justified in some circumstances on the basis of (a) infrequent exposure, or (b) significant benefit to those exposed or to society as a whole (NCRP, 2004). The proposed use of ADT systems appears to fit both of these alternative exceptions. The potential for repeated exposures to any single bystander appears to be quite low since ADT systems are intended to be used in a relatively limited number of incidents at random locations where there is some basis for believing that nuclear materials might be present, and it is highly unlikely that any one bystander might be present in more than one of those incidents. Furthermore, the intended benefit from use of ADT systems – detection and interdiction of nuclear weapons of mass destruction and SNM materials that could be used to make them – would accrue to society as a whole.

The 5 mSv per occurrence effective dose limit is also consistent with prior NCRP recommendations for the same limit on infrequent exposures to the public through use of other ionizing radiation-based systems for scanning cargo for nuclear materials or other contraband (NCRP, 2003a; 2007). The dose limits recommended here are also in agreement with Publication103 from the International Commission on Radiological Protection (ICRP 2007).

This document states that public exposures in planned exposure situations should not exceed an effective dose of 1 mSv per year, but allows higher effective exposures in special circumstances as long as the average in a 5 year period does not exceed 1 mSv per year. It is unlikely that any member of the public will be exposed more than once under the currently considered scenarios. If applications for the ADT system are contemplated in which the same individuals might be exposed more frequently during the course of a year, then the total limit for all occurrences should still not exceed 5 mSv.

It should be stressed that the 5 mSv effective dose limit for members of the public from ADT systems represents a recommended maximum effective dose for use in operational design of ADT technology and standard operating procedures. All reasonable efforts should be expended to obtain the needed information with doses that are as far below this limit as possible. In the application of the NCRP's recommendations to sources irradiating members of the public, the overriding considerations are those of justification and ALARA. Normally, application of these two principles will ensure that individuals are adequately protected (ICRP, 1977, 2007; NCRP, 1993).

This Commentary emphasizes the importance of justification of any practice as a key principle of radiation protection (Section 3.2). Justification becomes particularly important when the practice involves deliberate actions that could knowingly expose members of the public to significant levels of radiation without an ability to obtain informed consent or even inform them after the fact (Section 5). Simply meeting any of the limits specified in this Commentary does not obviate the operator's obligation to consider the appropriateness (including ethical, legal, and ALARA requirements) of any deployment of the technology.

The unusual characteristics of the proposed use of ADT systems add to the complexity and importance of the justification process. The possible use scenarios could vary so widely that some might be considered to be separate and distinct "practices" requiring their own justification arguments. For example, a scenario involving scanning a small boat suspected of carrying nuclear material would differ in many relevant aspects from one involving a search for a suspected nuclear device in a city. Separate justification analyses may need to be performed, and "rules of engagement" and operating principles developed, for such different scenarios. This would be consistent with NCRP's recommendation (NCRP, 2004) that in cases of infrequent exposure a 5 mSv dose limit is allowed; each occurrence should be justified independently of any other.

NCRP recommends that decisions concerning the design and use of ADT systems be informed by risk-benefit analyses based on the principles outlined in the report of the federal Interagency Steering Committee on Radiation Standards (ISCORS, 2008), discussed in Section 5.1.1. While the ISCORS report concerns activities associated with the use of ionizing radiation for security screening of humans, the same justification principles and procedures recommended in the report are applicable to decisions concerning ADT systems.

This Commentary's dose limit recommendation of 5 mSv for ADT systems is the same as the recommendation for members of the public for infrequent exposures It is possible that the final optimized design of the ADT system might not be able to meet the 5 mSv recommended dose limit. In this case, evaluation of the use of the system may fall outside the established system of protection. It is also possible, that interrogation of targets cannot be conducted without exceeding the 5 mSv limit to terrorists involved with the transport of SNM. ICRP (2007) recognizes that under emergency situations, normal public dose limits may not apply. The prevention of catastrophic consequences associated with detonation of a nuclear device might be considered to be such an emergency. In emergency situations, the ICRP (2007) recommends paying particular attention to the prevention of deterministic health effects and considering societal and economic impact in addition to health effects. Emergency plans should be made in advance with emphasis on the justification of use and optimization of protection strategies. These types of analyses are discussed in detail in Sections 5.1.1 and 5.1.2, respectively. Special operational considerations and dose limits could be considered assuming that the use of the system is deemed necessary and justified under national security and public safety requirements despite the greater risks.

4. Radiation Protection Requirements and Methods for Active Detection Technologies

The radiation characteristics of particle accelerators, including those technologies that might be of use in ADT systems, are well known. Their associated radiological hazards to personnel and the environment and their mitigation have been extensively discussed in a number of references (Cossairt, 2009; Cossairt et al., 2008; Fasso et al., 1990; ICRU, 1978; NCRP, 1989; 2003c; Patterson and Thomas, 1973; Sullivan, 1992; Swanson, 1979; Swanson and Thomas, 1990; Thomas and Stevenson, 1988). NCRP has provided extensive general guidance on radiation protection for particle accelerator facilities (NCRP, 2003c) and for radiation protection programs in general (NCRP, 1998).

A well-formulated radiation protection plan can ensure that radiation exposure is optimized for the worker, public and the environment. The plan, required by the U.S. Nuclear Regulatory Commission (NRC, 2009), U.S. Department of Energy (DOE, 2007), and many states (CRCPD, 2009), formalizes a program to ensure regulatory compliance and management oversight and accountability for the health and safety of personnel and for the security of radiation devices (IAEA, 1996). Although the ADTs deployed by the Department of Defense will likely be self-regulated (EPA, 2000), DoD follows the established regulatory and safety requirements. Aspects of routine radiation protection plans, such as safety design features, dosimetry and monitoring, training and record keeping, are comprehensively reviewed in other documents (NCRP, 1998). While it is essential for the users of the equipment to have the education, knowledge, skill, and judgment to use the equipment safely and effectively, automated systems provide assurance that appropriate safety responses are executed in a timely fashion. This Section focuses on those aspects of an ADT system radiation safety program that require special emphasis and planning, in particular, to prevent inadvertent entrance of any individuals into areas where exposure above the recommendations could be received.

4.1 Output Determinations

The output of a particle accelerator in the ADT, in terms of exposure rate, integrated exposure or pulse exposure, must be accurately measured before the system is put into use and reassessed at regular intervals. These measurements must be taken at fixed distances from the beam port and at various locations within and outside the beam field. These measurements must be verified for all beam technique factors, including acceleration voltage, tube current, filter material and thickness, and pulse durations that might be used in actual practice. These results must be reviewed periodically and used to predict the exposure of anyone inadvertently entering areas where exposures above the recommendations could be received.

Optimally, survey and monitoring instrumentation would be automated and intrinsic to the design of the system, collecting dose information simultaneously with operations. Given the usage of ADTs, it is unlikely that scenarios of usage would allow for extensive measurements with hand-held meters given the fact that temporal windows of opportunity for their use are likely to be short and radiation levels or ease of movement within the areas of concern might be prohibitive. Furthermore, it is improbable that conditions of operation including all relevant factors such as weather, terrain, etc. could be reconstructed with complete accuracy. The survey and monitoring functions should be integrated with the tracking of other operational parameters.

4.2 Interlock Systems

Interlock systems are necessary to monitor and help exclude operating personnel and bystanders from receiving high exposures. ADT systems must be designed to be transportable. Unlike stationary systems, ADTs will be unable to exclude members of the public from the vicinity by means of building access restrictions, fences, etc. Size and weight limitations of a transportable system may preclude the heavy shielding needed to control prompt radiation. Consequently, these systems may require a monitoring system capable of recording radiation levels to nearby areas or personnel.

Assurance must be maintained that these systems can and will quickly and automatically terminate the exposure whenever an individual wanders close to or enters the areas where exposures above the recommendations could be received. As with output determinations, all radiation control interlock systems coupled to the ADT system must be tested and verified on a routine basis. Critical interlocks where access to radiation fields would cause dose or dose rate limits to be exceeded must be fail-safe. In addition to interlocks, other safety systems should be tested and, where applicable, be adapted for use with ADTs to alert the operators to changing distances from the accelerator to the object under interrogation or to warn when bystanders or nontargeted vehicles are approaching the areas where exposures above the recommendations could be received. Testing needs to verify that the detectors can accurately detect intrusions into the areas where exposures above the recommendations could be received, will interface correctly with the ADT, and will provide appropriate alerts to the operators.

Many possible approaches are available for remote monitoring and interlock mechanisms. How many of these systems might be used with any given ADT system would depend on how effective and reliable they prove to be. The possibilities include:

- **Range Finders.** Range finders could provide accurate feedback on distances to interrogated objects and automatically adjust the beam output to provide the optimal exposure for effective interrogation. This would be especially important with objects in motion such as boats on water or transport vehicles on land. Their use could help to ensure that radiation output would not be excessively high and that potential exposures would be limited to or lower than those recommended in this Commentary.
- **Motion Detectors.** Motion detectors could be used to control and terminate beam outputs before individuals enter the beam areas where exposures above the recommendations could be received. They could also be able to detect other vehicles, such as boats, trucks or automobiles approaching these areas.
- **Infrared Detectors.** Infrared detectors might also prove useful for detecting individuals before entering the beam areas where exposures above the recommendations could be received or sensing individuals in these areas when visibility is poor or the ADT system is being used during low visibility conditions (e.g., in fog or after dark.).

4.3 Emergency Response

Given the nature of ADTs, the possibility of exposures to prompt (high dose-rate) radiation, notably the interrogating beams, special consideration for emergency response is warranted. An emergency response plan for these devices needs to include considerations commensurate with their usage that are well-planned in advance to ensure that proper actions are taken in the event of any undesirable occurrence. Many of the same actions specified for other types of radiological installations and other particle accelerators, including loss of radioactive materials, contamination events, and potential overexposure to radiation for both workers and members of the public will be required for ADT systems emergency response considerations.

Previously, NCRP has provided extensive, detailed guidance on the preparation of emergency plans, most of which is directly adaptable to the needs of ADT systems (NCRP, 1991; 1998).

Because there is a universally recognized duty not to cause serious harm to innocent bystanders (Section 5.1), operators of ADT systems have the responsibility of ensuring that individuals do not inadvertently enter areas where exposures above the recommendations could be received. To achieve this goal, the use of physical barriers, where possible, and the types of sensing and interlocking systems discussed in Section 4.2 will be necessary; the devices to be used may depend on the specific scenario for use of ADT systems. If the interlock or control systems fail and individuals have the potential to receive exposure, then specific actions must be taken immediately. These actions include termination of the radiation output from the system, detention of the unintentionally exposed individual if possible, immediate determination of exposure to the affected individual(s), appropriate attention to any radiation injuries, and investigation and corrective action. In particular for ADTs, protocols need to be developed before deployment that provide for reliable estimates of doses that could be received by individuals under all possible operational scenarios and potential situations that would result in unintentional exposure.

4.4 Determination of Doses to Individuals and Notification

If it is estimated that an individual may have been exposed to radiation above the recommended limits, immediate steps must be taken to determine the delivered dose, how best to inform them of the exposure and, where indicated, appropriate action that must be taken. Given the intended use of ADTs, it is possible that disclosure of radiation exposure to bystanders in the interrogation site could compromise the mission. Plans must be developed prior to deployment for how such exposures would be handled. Where appropriate, the operators of the ADT must ensure that exposed individual(s) receive proper clinical attention and that their radiation exposure-related needs are addressed. Where immediate medical attention is not required, it would be prudent to refer individuals to clinical experts for examination, biodosimetric assessment, such as chromosome analysis, and long-term follow up.

Communications, exposure determination, follow-up actions, and clinical attention for the exposed individuals would be much more difficult for bystanders who quickly pass into and out of the areas where exposures above the recommendations could be received, such as would be the case for individuals driving down highways or moving through the interrogation area in boats. For this reason, it is extremely important that the operators of ADT systems be diligent in using an effective system to ensure that individuals do not pass through these areas in such situations.

4.5 Records and Documentation

Because of the inherent potential for unintended exposures, thorough record keeping for ADT usage is essential. NCRP Report No. 114 (1992), Maintaining Radiation Protection Records, describes in detail the development and retention requirements for adequate record keeping. Since the ADTs are mobile, configurations may differ from one usage to another. Documentation of the specifics for each location and usage is critical. These records should include: photographs, videos and facility diagrams for fixed and remote locations, controlled activities area, access controls, monitoring or survey records for radiation areas, instrumentation, protective equipment, quality assurance, and accident and incident investigation findings. Records of assessments performed to demonstrate that doses are being kept as low as reasonably achievable (ALARA) should also be retained.

Pertinent records also include, whenever possible: (1) identification of the individual(s) exposed, (2) the times and dates of exposure, (3) the maximum estimated effective dose or the actual effective dose per exposure, if known, and (4) the cumulative effective dose to the individual(s) over the past year. Radiation safety records can be used for a variety of purposes including evaluation of the radiation safety program to ensure effective program operation, evidence of regulatory or administrative compliance, data for epidemiologic studies, and information for making or contesting claims for radiation-induced injury.

Environmental and effluent (if applicable) radiation measurements and analyses are made to allow accurate, systematic assessments of exposure. Records are used to determine compliance, evaluate changes in environmental concentrations, and estimate population and individual exposures. Specific examples of environmental records can be found in NCRP Report No. 114 (1992); the overview of records includes preoperational and operational monitoring records; release and dose assessment and off-site or special studies (if applicable).

Records should be maintained in anticipation of future liability from radiation exposure. The accuracy and completeness of the records that can be used to estimate the radiation dose will be essential. All situations involving radiation have the potential to incur personal injury lawsuits. Consideration should be given to assuring the records contain accurate reliable information and that relevant records are maintained and retrievable. Effective documentation and retention of records can assist in reconstruction of the exposure and aid in the determination of dose from exposure years after the event.

If it is determined that individuals have been exposed to radiation in the radiation control zone, they must be advised of the exposure received, the potential consequences of such exposure (in lay terms), and the additional steps that might be necessary and in their best interest. All concerns of the individuals will need to be addressed and appropriate records of these conversations must be made. Documentation of any exposures must be thorough, and provide evidence that all appropriate steps were taken to control the situation, to evaluate the exposure involved, to provide appropriate support for the individual(s) and to ensure indicated follow-up was provided.

4.6 Environmental Considerations

Environmental impacts must also be considered when employing ADT systems. NCRP (1991) recommended no more than 10 mGy d^{-1} radiation exposure to the maximally exposed aquatic biota. This recommendation was based chiefly on reproductive sustainability at these radiation levels. It endorsed the previous ICRP (1977) statement that, "if man is adequately protected, then other living things are also likely to be sufficiently protected."

IAEA (1992) suggests chronic dose limits to terrestrial plants and animals of 1 mGy d^{-1} and to aquatic organisms of 10 mGy d^{-1}. IAEA (1992) also noted, "There is no convincing evidence from the scientific literature that chronic radiation dose rates below 1 mGy d^{-1} will harm animal or plant populations." A chronic exposure to the environment would be highly unlikely from these mobile units. Clearly, the only cases where environmental impact would limit exposure is when the systems are used in stationary positions (so that individual human exposure would be limited, but perhaps nearby organisms could be continuously exposed), or when there is higher coincident exposure to the biota than the humans. The latter case would be true only when there is intervening biota in the interrogation beam (not technically feasible using the ADT systems) or from exposure to the source (e.g., accelerator) itself. "Skyshine" (scattering off of the atmosphere) is of insufficient magnitude to consider for the purposes of biota exposure.

Stationary ADT systems would be the only systems that would have the opportunity for exposure of biota for a continuous period of time. Shielding around stationary ADT systems should be designed such that exposure to local biota is considered. Shielding will be designed to sufficiently protect workers in the vicinity, as well as to protect passers-by in the case of a system placed near the public. The only reasonable exposure to biota would be through bulk shielding into the soil. It is difficult to conceive of a stationary system being placed in the immediate vicinity of an endangered population of any plant or animal, so this Commentary does not place any specific restrictions on dose rates into the soil.

It is possible, for a stationary ADT system, that the interrogation beam could continuously expose soil, rock, and/or building materials such that they could become radioactive and contribute to the exposure of personnel. The capability for the ADT system to activate these materials is a function of the type and energy of the beam. Stationary systems should be evaluated, along with the types of local materials to determine the propensity for activation.

5. Guiding Principles for Active Detection Technology Use

The use of ADTs could expose individuals in the general public (bystanders) to ionizing radiation. By necessity of the concept of operations of ADT systems, these inadvertent exposures would be without prior consent. An individual would be unable to make an informed decision regarding risks and benefits. This contrasts with other uses of radiation such as medical diagnostics and therapeutics where the benefits are clear and the risks are knowingly assumed. Unlike radiation workers, such individuals are not assuming the risk in return for employment. It differs, too, from other screening approaches where one could opt for a different mode of transportation or physical search in lieu of exposure. Consequently, the use of ADTs demands a thorough assessment of risks, benefits (Section 5.1.1), and procedures available to limit adverse effects (Section 5.1.2), as well as public disclosures before and after usage of the technology (Section 5.1.3).

5.1 Ethical Principles

Ethical principles prescribe that no individual should be put at undue risk of harm. Exceptions are possible but must be carefully considered. Justification of goals, minimization of risk, consent, disclosure of risk, and remediation are non-mutually exclusive concepts that must be considered. The principles of radiation protection described in Section 3.2 are consistent with these ethical considerations.

5.1.1 Justification of Goals

The first principle of radiation protection (i.e., justification) refers to the broad societal decision made either formally or informally and based on the conclusion that the expected benefits to society exceed the overall societal cost. The overall justification for use of ADTs for specific security applications and what constitutes a net benefit to society are broad questions, outside NCRP's role as defined by its Congressional charter. NCRP can provide guidance on radiation risks and some of the considerations integral to making a societal decision, but cannot render an opinion of the net benefit or cost.

5.1.1.1 Risk Benefit Ratio. As a rule, benefits should exceed risks. However, even significant risks may be justified if the benefits of using the device are substantial.

If using the ADT conferred a very high potential benefit (e.g., averting the detonation of a nuclear device), then exposing bystanders to risks could be justified. In cases where the risk to individuals is expected to be significant, the benefits associated with interrogating a specific targeted object would need to be substantial, and known with a high level of confidence.

Conversely, interrogating targeted objects with low likelihood of containing SNM would confer less likelihood of benefit, and would call for assurances that the risks of exposing bystanders were low. For example, if the ADT system was used for random surveillance of a large number of targeted objects with low probability of containing SNM, the potential benefit from each use would be low and the risk/benefit ratio would rise. If the system had very low sensitivity or specificity, it would be more difficult to justify exposing bystanders to even low risks.

If the use of the ADT system involves significant risks, there should be assurance that safer, alternative methods of detecting SNM are not feasible or appropriate. Whether or not the increase in risk of using the ADTs is justified depends, in part, on the cost, efficiency and efficacy of traditional inspection techniques. It is unethical to simply assume that a technologic method is superior to human activity without adequate examination.

Few if any technologies are without risk, so reduction of risk to zero is generally not practical. In all cases, all reasonable efforts to minimize the risk should be taken. For example, careful planning for the use of an ADT system would include the use of appropriate interlocks to automatically interrupt the beam when a person is in range (Section 4.2). Similarly, the radiation output of the beam should be a low as possible, consistent with achieving its purpose.

5.1.1.2 Guidelines for Risk Benefit Analysis. The federal Interagency Steering Committee on Radiation Standards provides some well-considered guidelines for a risk benefit analysis in ISCORS (2008). The recommended steps include:

1. Quantification of the probability and consequences of the threat. While precise numbers may be difficult, if not impossible, to assign, a relative scale using categories such as certain, very likely, possible, not likely or never may suffice. The estimates of likelihood and impact of a threat should be supported by data such as the amount of contraband missing or intelligence reports on terrorist activity.

2. Definition of the desired benefits of using the radiation device. Considerations include: the requirements for use, the expected impact on the probability of the threat, the consequences of inconclusive results and the follow-up required, the success rate required from the technology, and an assessment of who benefits and in what way.

3. Assessment of the radiation risks from using the technology. A documented analysis, developed for each scenario, should be reviewed in an independent office by technically knowledgeable individuals. Many of the considerations, such as dose limits for operators and bystanders, communication issues, and safety requirements are described in this Commentary.

5.1.2 Risk Optimization

The second principle of radiation protection, optimization, requires that radiation exposure be no higher than necessary to achieve the goal. This is the as low as (is) reasonably achievable, or ALARA, principle. Every institution and organization that uses regulated devices that produce ionizing radiation should provide a program plan that specifies the policies and practices that are necessary to control radiation exposures to its employees and the public within the prescribed dose limits and to exposure levels that meet the ALARA principle. The size and scope of the program should be commensurate with the potential hazards (NCRP, 1998).

Even at very low exposure levels, if simple, low-cost, and safe approaches could result in still lower exposures while continuing to achieve the required outcome, ALARA considerations would indicate that such means should be implemented. However, not all dose reductions can be achieved with equal ease or resource expenditure. Consistent with ALARA, doses need only be kept to levels which are as low as "reasonably" achievable in recognition that further reduction below some level cannot be rationally supported because the intended benefit would not be obtained, or because the cost (i.e., the sacrifice of other measurable benefits) or increased overall risk would be unreasonable (NCRP, 1990).

5.1.3 Disclosure of Risk

There is generally an ethical responsibility to disclose the risks associated with an exposure to the affected population. Communication, possibly before and certainly after the exposure, should be pursued as diligently as possible. Prior disclosure to the members of the public about the potential for radiation exposure from ADT systems, however, may be impossible in certain operational circumstances.

Informed consent allows an individual to decide to assume a risk. Such consent must be based on an adequate understanding of the potential consequences, with the freedom to refuse exposure. If there was a plausible risk of significant harm, particularly to innocent bystanders, consent might take different forms. If the risk was low but plausible and a class of individuals at risk could be identified, implied consent might apply if those at risk are provided with general information in advance so that they could choose to opt out of working in that environment. Under the circumstances considered for use of ADTs, it may not be possible to acquire specific informed consent prior to exposure. This makes it imperative that justification and optimization be carefully considered prior to exposure and that post-exposure disclosure and reparation options be in place if at all possible.

Another approach to consent is general consent by the public, which could be through general information programs by the government and the free flow of information to the mass media. To the degree that general awareness of the system would not interfere with its effectiveness, openness is preferable to secrecy. Whether or not public consent, or at least acquiescence, should be required is in part related to the degree of risk, but also to the perception of risk, as fear can be unrelated to risk. Recent discussions of enhancing examinations of airport passengers with more invasive scanning devices suggests the public is generally tolerant of minimal risks of radiation if they provide a substantial decrease in the risk of harm from terrorists (for example, see Capehart, 2010; Meek and Sisk, 2009). The limitations on informed consent for use of ADT systems confer particular importance to communications designed to inform decisions about the development and deployment of such systems (Section 5.2).

Disclosures post-exposure are important for minimization of adverse consequences of exposures. If a person was inadvertently exposed, and there was more than a trivial risk of harm, there would generally be an obligation to inform that person. The duty to disclose would presumably apply to citizens of other countries, regardless of whether the devices were used on United States or foreign soil or waters. Post-exposure notification of exposed and potentially exposed individuals would allow them to take any available precautionary steps to limit harm and ensure that they would be able to recognize any possible early symptoms and seek medical attention (Section 4). To be effective, records of device use, dosimetry, and medical follow up will be essential. Additional discussion of communication issues is in Section 5.2.

5.1.4 Reparation

Another basic ethical principle is the obligation to provide reparations if one causes harm to an innocent person. Reparations can take the form of financial compensation for all potentially exposed persons or might be limited to compensation should injury actually occur. In addition, legal precedent has been established and the mechanisms for dealing with such claims have been developed. Experiences with other potentially toxic exposures might be useful in guiding deployment and communication practice. Examples are reviewed in Martin (2009), Panangala and Weimer (2009), Presidential Advisory Committee on Gulf War Veterans' Illnesses (1996), NA/NRC (2003), and IOM (1996). The U.S. Government should be prepared for the possibility that at some point, perhaps long after exposure, a range of individuals could request or demand reparations.

Questions of accountability arise if there is a risk of serious harm. Decisions on the requirements for use in each scenario need to be made at an appropriate level of responsibility. If the risk was trivial, then decisions about deployment might be appropriately made at a lower level, but in any case it should be clear as to who is authorized to deploy the device in a specific location. If it was deployed in a foreign country, there would be an obligation to follow international guidelines regarding coordination with foreign governments.

5.2 Communication

There are four potential audiences for which communication strategies should be considered: decision-makers who will be asked to fund research and development, the broader public/media, parties (including DTRA) who authorize or employ the technology, and individuals who may be exposed through operations. These classes of individuals may not always be exclusive. Communicating risks to individuals operating ADT systems should be part of the training and design, as discussed above.

For each of these audiences, communication strategies should be considered for two distinct stages: communication during funding, research, and development (ex ante), and communication strategies associated with deployment (ex post). Ex ante communication can be participatory, while ex post communication is more likely to be one-directional. Ex ante communication will have to carefully balance ethical considerations and the need to not compromise informants or low-visibility/unannounced operations. There are several important categories of ex ante communication:

- Communications directed to decision makers, the media, and public to provide them general information about ADT systems that can inform decisions about to the development and implementation of such systems.
- Communications directed to training ADT system operators and support staff, following established guidelines for work consistent with radiation safety protection.
- Communications directed to those who will make deployment decisions in the field.
- Communications directed to members of the public who are in an area where such systems might be operated. Because of the intended uses of ADTs, informed consent (even implied) may not be possible (Section 5.1.3).

Ex post communication would take place largely in the form of disclosure following use of ADT system, and should follow standard disclosure practices. Consistent with previous NCRP commentaries dealing with ionizing radiation scanning systems, this Commentary recommends that the authority responsible for the system provide information about the exposure and the resulting potential increase in cancer risk to individuals known to have been exposed. However, this might not be possible or desirable in some circumstances (e.g., if revelation of the fact that an ADT system had been used in a particular circumstance might compromise the source of the intelligence that led to that use, or if the information is nonactionable). Ex ante information should be provided only following culturally and socially appropriate consultation and should include information about known and suspected exposures, the known and expected effects of those exposures, and the opportunities for individuals to mitigate exposures and effects. Such information should be easy to understand (i.e., in layman's terms) and presented in a language understood by the individual or through a translator, where practical.

5.2.1 Stakeholder Involvement

Experiences with other technologies involving radiation suggest that stakeholder engagement should take place early and often. The most effective communication among stakeholders is "mutual and recursive," and should include all "interested and affected parties" (NA/NRC, 1996). For ADTs, stakeholders include all four groups listed above.[3] While it can be a challenge to develop this sort of public interaction, as well as to balance the need for public confidence with concerns about secrecy, public involvement is essential for reasons of both ethics (Section 5.1) and efficacy. That is, the development of technologies involving radiation can be derailed by inadequate attention to concerns of decision-makers, the media, and public officials. Involving all groups as early as possible should improve the chances of developing broadly accepted and useful technologies. This will be particularly true in cases where members of the public may or will be exposed to radiation from ADT. Since the bystanders who may be exposed during deployment are unidentifiable, development of messages, a priori, will be necessary. Messages developed for this purpose should attend to the literature on effective risk communication practices (see e.g., Lundgren and McMakin, 2009; Slovic, 2000), and should be vetted and tested beforehand (Wray et al., 2008).

As individual technologies are developed, DTRA should pursue public engagement. An appropriate strategy would be to develop standard practices for public involvement, including the range of individuals who can provide useful input and guidance, the topics that they will address, and the security clearance appropriate to different public engagements. An important operating principle of stakeholder involvement is that stakeholders—including media and decision makers—should not be seen as recipients of communication, but as active partners in decisions about the appropriateness of different technologies. The acceptability of risk in different contexts is a values decision and should be assessed by the public or its selected representatives.

[3] Although enemy combatants and terrorists trying to deploy nuclear devices are very clearly "interested parties", they are not included here as stakeholders (Weimer and Vining, 2005).

5.2.2 Locus of Responsibility for Communication

One particular goal of public involvement will be to develop a priori standards of communication for engagement. This should be done under the auspices of a single agency responsible for formulating generic messages for each technology/deployment scenario. Having a single responsible agency should allow for a consistent communication approach to be followed for all technology/deployment combinations. Several U.S. organizations (including U.S. Department of Health and Human Services) are developing similar materials that would be valuable.

Communication needs and standards developed by the agency should be included in (and should influence the development of) rules of engagement for each technology/deployment. This agency should also be responsible (either directly or by issuing guidance) for:

- Training of public communicators for both pre- and post-deployment situations;
- Identifying the appropriate role of informed consent for different deployment scenarios;
- Identifying legal requirements for communication and disclosure;
- Ensuring that disclosures identify when actual exposures are or are not consistent with a priori exposure expectations;
- Developing communication strategies capable of differentiating between dose and dose rate, since in ADT applications dose rate is expected to be high and in nanosecond pulses; and
- Determining what conditions will trigger the need to communicate risk, and to which individuals/populations.

Several of these topics are explored below.

5.2.3 Communication Standards

5.2.3.1 Effective Risk Communication Practices. Extensive experience and research within the public health and risk analysis communities provide guidance on both how to design appropriate communication approaches for different risks and audiences and how individuals will interpret messages. Effective risk communication must consider several factors.

First, it must be culturally appropriate. That is, different audiences receive and transmit messages through cultural and social channels and interpret them through cultural and social lenses. As groups and individuals who might or will be exposed are identified, messages relevant to those populations should be developed.

Second, messages must be developed that account for the language spoken or read by the relevant audiences, as well as the educational and literacy levels of those audiences.

Third, communication strategies should be specific to the technology deployed. That is, as each new technology/deployment combination is developed, information about the risks associated with that technology should be developed. Since events involving radiation pose special psychosocial and risk communication challenges, this needs to be taken into account in developing effective risk communication (Becker, 2004, 2009).

Fourth, communication strategies should be consistent across all uses. To this end, as each technology and deployment is developed, the communications strategy and content should be maintained at a central location or authority. This does not mean that communication should not evolve and improve. Where relevant, lessons learned in novel arenas should be transferred back to and adopted for subsequent applications.

Finally, communication strategies should be specific about the range of risks and benefits to exposed populations. Wherever risks within a population may be unevenly distributed, communication strategies should be targeted to individuals. Individual risk may vary as a function of exposure, susceptibility to adverse outcomes once exposed, or both. Individuals who are at greater risk may be identifiable, but in some cases it may only be known that some individuals are at greater risk, without knowing who those individuals are.

5.2.3.2 <u>Use of Analogies for Specific Practices</u>. As specific technology and deployment scenarios are developed, appropriate analogies for communication should be explored. Several examples might include:

1. The aerial spraying of Malathion in California to manage the Mediterranean fruit fly. In this case, many individuals were exposed in order to achieve a substantial public good—the elimination of a serious pest to California's citrus industry. This analogy would be appropriate when numerous individuals in the United States are or may be exposed to ADT in the pursuit of illicit nuclear materials. A potential weakness of the analogy is that ex ante communication, which was practiced in the Malathion case, might alert the individuals with illicit materials.

2. The spraying of Agent Orange during the Vietnam War and the use of depleted uranium in shells in Bosnia and elsewhere. In both of these cases, U.S. military personnel were exposed in two ways: some individuals were involved in deploying the technologies, others were exposed following deployment. Enemy combatants and local noncombatants were exposed during and following deployment. Communication failures prior to and following exposures may have contributed to the continuing controversies about both health impacts of exposures and reparations for alleged effects.

3. Another analogy from the public safety realm might be "hot pursuit," where an uninformed public is exposed to possible traffic accident risk in order to deal with a known or strongly suspected threat. The weakness of this analogy is that individuals know whether they have experienced adverse effects from hot pursuit, while they might not for the case of ADT.

4. A final example might be the current use of predator drones and other unmanned military strikes. Here the exposed population is expected to include high-threat individuals or material, but may include noncombatants. The audience might include numerous groups within the region where the technology is deployed, in the United States and elsewhere. The lesson from this analogy is that prior communication about specifics would undermine the deployment; there are multiple audiences with diverse concerns, and the individuals exposed represent only a very small fraction of the relevant set of audiences.

Each of the above analogies has multiple relevant audiences: U.S. personnel in several settings (those using the technology, those exposed to the technology during related or nonrelated activities), enemy combatants, local noncombatants, regional populations and governments, individuals and groups (including government) within the United States, and third parties including other national governments and multinational agencies, as well as nongovernmental organizations. An extensive list of analogies is inappropriate for this Commentary, but as applications for ADTs are developed, communication analogs for those applications should be developed in parallel. While analogies are useful, it is important to acknowledge that aspects of exposures from ADTs are certain to be novel.

5.2.4 Communication with Foreign Countries

Since one possible use of ADT systems by the U.S, Department of Defense is for the detection of materials located on foreign soil and in international waters, special care should be given to how, under what conditions, and to whom risks associated with ADT systems should be communicated. International cooperation will likely be necessary. Many of the above conditions are relevant: risk communication may include policy makers and elected officials, individuals cooperating with U.S. personnel, and civilians in foreign countries. The use of ADTs in such contexts may represent a unique condition. However, there may be both relevant analogies (e.g., the unmanned strikes mentioned above) and applicable international policy norms and standards.

5.3 Other Considerations in Active Detection Technology Development

While the intended use for the ADTs is detection, conceivably their capabilities can be expanded to purposes not intended or anticipated in their early stages. Although not an objective for ADT development, ADT technology could conceivably be transformed for alternative uses such as a weapon system. Acknowledgement of the possibilities for redirection and open commitment to use of the systems solely for purposes of detection could provide reassurances to the public.

6. Summary and Conclusions

6.1 Active Detection Technologies

The proposed ADT systems differ in significant respects from the security systems considered in prior NCRP Commentaries, raising unusual and challenging issues for the application of the principles of radiological protection.

- The ADT systems under consideration are intended only for a specific and high-priority national security application. An analysis of the societal benefits of ADT systems as part of the justification process is likely to include a reduction in the threat of a nuclear detonation, a cataclysmic event generally acknowledged to be worthy of extraordinary preventive measures.[4]
- Because the range of operational capabilities of the proposed ADT systems is unknown at this time, it is not clear what radiation levels would be required for effective detection of nuclear materials and hence what levels of radiation might be involved in unintended exposures. Information about these levels will be needed for the appropriate application of the principles of justification and ALARA.
- The expected distance between ADT systems and the objects for inspection might make it impossible to limit access to the irradiated zone and might lead to radiation levels to accidentally exposed bystanders near the device that are much higher than those associated with the other security systems NCRP has considered.

6.2 Risk Benefit Analysis

One of the guiding principles of health protection is the need to justify any activity that involves potential radiation exposures to ensure that the expected benefits to society exceed the overall societal cost (i.e., justification). Justification is particularly important when the practice involves deliberate actions that could knowingly expose members of the public to significant

[4]Possible scenarios involving the use of ADT systems under conditions of imminent and grave threats to national security, or under uniquely military environments, for prevention of catastrophic consequences, may be considered emergency situations in which normal public limits on radiation dose do not apply but strong justification and optimization of protective strategies are emphasized (see ICRP, 2007).

levels of radiation without an ability to obtain informed consent or even inform them after the fact, as might occur with use of ADT systems. The possible scenarios for use of ADT systems could vary so widely that some might be considered to be separate and distinct “practices” requiring their own justification arguments.

Recommendation: *NCRP recommends that decisions concerning the design and use of ADT systems be informed by risk-benefit analyses based on the principles outlined by the federal Interagency Steering Committee on Radiation Standards. Recommended steps include: (1) quantification of the threat, (2) definition of the desired benefits, and (3) assessment of radiation risks. Decisions on the requirements for use in each scenario need to be made at an appropriate level of responsibility.*

6.3 Optimizing Exposures: Automatic Termination Mechanisms

Health protection guidelines also address the need to ensure that the total societal cost of the justified activities, in terms of radiation exposure, is as low as is reasonably achievable, economic and social factors being taken into account (the ALARA principle). This requires optimization to achieve the greatest societal benefits while keeping costs in resources and health risks as low as possible. Inherent in this ALARA principle is the need to prevent unintended exposures to personnel and bystanders. Unlike stationary systems, ADTs will be unable to exclude members of the public from the vicinity by means of physical barriers.

Recommendation: *Mechanisms must be established to monitor radiation dose in nearby areas and to quickly and automatically terminate an exposure if an individual or vehicle approaches the radiation zone. These mechanisms need to be intrinsic to the design of the ADT system, coupled to the radiation generating system to ensure automatic cutoff and to provide an alert to the operators of the ADT. Furthermore, to ensure that the ADT system is emitting radiation that will be effective but as low as possible, the system will need to detect changing distances between the source and the targeted object. It is important that these safety systems be tested and all systems verified on a regular basis.*

6.4 Dose Limits

Proper radiation protection considerations will result in adhering to dose limits for radiation exposure to occupationally exposed workers and the public. These considerations will require a written radiation protection plan, a thorough understanding of the radiation source, proper monitoring, safety systems (both administrative and engineered), emergency response plans, and record-keeping.

Dose limits for occupational exposure are clearly established by regulation . Local, state, and federal laws may all apply. Previous recommendations of the NCRP [for example, in NCRP Report No. 116 (1993)], for occupationally exposed workers are not revised in this Commentary, as ADT systems do not pose unique hazards for workers. ADT systems do pose unique hazards to members of the public who may, despite reasonable efforts, be exposed to ADT radiation sources.

Recommendation: *The effective dose to a bystander exposed to radiation from an ADT system should not exceed 5 mSv per event, consistent with prior NCRP recommendations for application of the same limit to infrequent exposures to the public through use of other ionizing radiation-based systems for scanning cargo for nuclear materials or other contraband. This limit should apply to the total dose a bystander might receive during a single inspection event, which might involve multiple exposures to the bystander or during multiple inspection events over the course of a single year.*

The 5 mSv per event dose limit represents a recommended maximum effective dose for use in operational design of ADT technology and standard operating procedures. All efforts should be made to obtain the needed security screening information with doses to bystanders that are as far below this limit as possible, consistent with the application of the key radiation protection principles of justification and ALARA.

This Committee has not made specific recommendations regarding dose limits for environmental receptors because the limits recommended for humans, along with reasonable shielding design, are sufficient to protect the environment under all anticipated exposure conditions.

6.5 Ethics and Communication

Ethical issues associated with other technologies that have the potential to expose individuals to radiation apply to ADTs. These include a need for appropriate and timely communication, the balancing of risks and benefits, the application of the ALARA principle (radiation risks should be as low as is reasonably achievable), and reparations for potential harm to human health. ADTs differ from other radiation exposures in that exposures will typically NOT allow specific prior informed consent. However, ethical principles need to be considered.

Communication strategies should be geared towards four audiences: decision-makers who will be asked to fund research and development, the broader public and news media, parties (including DTRA) who authorize or employ the technology, and individuals who may be exposed through operations, for each of whom <u>ex ante</u> and <u>ex post</u> practices and norms are established. Standard practices for communicating exposures must be balanced with the need for secrecy and efficacy of detection of illicit transport of SNM. As much as possible, communication should be multidirectional and include the broadest possible set of stakeholders. The obligation to establish communication falls to the organization deploying the technology, which should identify and authorize a responsible agent as early in the technology development process as possible. Effective communication should include consideration of best practices, application of analogies, and the potential need to communicate with foreign governments.

Recommendation: *In all cases, risk-benefit assessment, appropriate communication, application of the ALARA principle, and approval by qualified authorities at the highest possible level are minimum expectations in the use of ADT systems. Communications using "best practices" should be distributed as broadly as possible, within the constraints of ADT usage.*

Appendix A

Health Effects of Radiation

The serious radiation-induced effects of concern in radiation protection fall into two general categories: deterministic and stochastic effects.

A.1 Deterministic Effects

A deterministic effect is one that increases in severity with increasing radiation dose above a threshold dose. The severity increases because of damage to an increasing number of cells. Deterministic effects occur only after relatively large doses (on the order of 1 Gy and higher), but the threshold dose and the severity of the effects may be influenced by individual susceptibility and other factors. The question of radiation dose thresholds for deterministic effects is complex and the magnitude of the apparent threshold depends on the specific biological endpoint and the ability to detect it. However, if the endpoints of concern are restricted to those that are clinically significant, dose limits can be selected to be less than the threshold values for these effects (NCRP, 1993).

A.2 Stochastic Effects

A stochastic effect is one for which the probability of the effect occurring increases with increasing absorbed dose, while the severity of the effect is independent of the magnitude of the absorbed dose to the affected individuals. A stochastic effect is one in which the probability of occurrence, but not the severity of the disease, increases with absorbed dose. (e.g., cancer and hereditary effects). There are differences in the risk for an effect from a given absorbed dose that are dependent on individual factors such as age and gender. A stochastic effect is assumed to have no threshold dose, although currently available observations in population exposure studies do not exclude the possibility of no effect at very low doses above background. The induction of stochastic effects is considered to be the principal effect that may occur following exposure to low doses of ionizing radiation (NCRP, 1993).

For radiation protection purposes, while acknowledging that uncertainty exists in dose-response relationships in the low dose range NCRP assumes: (1) that the risk for stochastic effects is proportional to dose without threshold throughout the range of dose and dose rates of importance in routine radiation protection, and (2) that the risk accumulates linearly with dose (NCRP, 1993).

A.2.1 Genetic (Hereditary) Risk

Calculations of genetic risk from radiation exposure of humans have been provided by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2001). The approach used represents a departure from approaches used for previous estimates, and has taken advantage of the increasing knowledge of the molecular basis of inherited diseases. Thus, the UNSCEAR (2001) genetic risk estimates are based on the use of human spontaneous mutation data (as opposed to mouse data) and radiation-induced mouse mutation data. The lack of observed inherited effects for radiation-exposed humans still necessitates the use of data for radiation-induced mutations in the mouse.

Based on recent data on radiation-induced germ cell mutations and human genetic diseases, ICRP (2007) revised their assessment of hereditary effects. The tissue-weighing factor for gonadal tissue was significantly reduced, with a resultant six- to eight fold decrease in the risk coefficients for heritable risk. Despite this decrease, ICRP (2007) continues to include heritable effects in their consideration of total radiation effect.

Overall, the predicted risks for the first generation mutations (3,000 to 4,700 cases per million progeny per gray of parental radiation (i.e., per gray of gonadal absorbed dose) are about 0.4 to 0.6 % of the spontaneous frequency (730,000 per million) (UNSCEAR, 2001). These risks only rise by a very small increment if the population in every generation receives 1 Gy of parental radiation.

A.2.2 Cancer Risks Attributable to Low Doses of Ionizing Radiation

The question of the biological effects of low levels of radiation has been investigated and debated for decades. There are data from the available human epidemiological studies that suggest equivalent doses as low as 50 mSv in 1 y or as low as 100 mSv over a lifetime (in addition to natural background) may produce an increased risk of deleterious consequences in humans, both in terms of cancer and noncancer endpoints (Little et al., 2009; Tubiana et al., 2009). At lower doses, progressively larger epidemiological studies would be required to evaluate the risk. For example, if the excess risk was proportional to the radiation dose and if a sample size of 500 persons was needed to determine the effect of a high exposure [e.g., 1,000 mSv, a sample of 50,000 might be needed for a 100 mSv dose, and about five million for a 10 mSv dose (Land, 1980; Pochin, 1976)]. In other words, to obtain statistical precision and power, the necessary sample size increases approximately as the inverse square of the dose. In considering the effects of low doses of radiation, it is also important to make the distinction between doses delivered acutely over a very short period of time (such as the atomic-bomb exposures), and protracted exposure (such as occupational exposure). Generally speaking, protracted exposures to ionizing radiation, especially sparsely ionizing radiation such as x or gamma rays, seem to be associated with lower risks than those resulting from an acute exposure at the same total dose (ICRP, 2007; NCRP, 1980; 1993).

A.2.3 Acute Low-Dose Exposures

There are data for exposed human populations that suggest an increase in risk for cancer mortality at acute equivalent doses as low as 50 mSv (Doll and Wakeford, 1997; Pierce and Preston, 2000; Pierce et al., 1996; Ron et al., 1995). The sensitivity of the studies does not allow for direct estimates of cancer risk at lower doses; lack of estimates does not imply any conclusion, one way or another, on whether there are increases in cancer risk at these lower acute doses.

A.2.4 Protracted Low-Dose Exposures

There are data that suggest an increase in some cancer risks in humans for protracted equivalent doses as low as 100 mSv (Krestinina et al., 2005). These approximate dose thresholds tend to be somewhat higher than those for acute exposures. Again, the fact that cancer risks cannot be estimated directly at lower doses does not imply any conclusion on whether there actually are increases in cancer risk at these lower protracted doses. The low-dose exposures associated with the ionizing radiation scanning systems used for screening humans for security purposes will generally be well separated in time and can be categorized as protracted low-dose exposures.

A.2.5 Extrapolation of Risks to Lower Doses

At absorbed doses below which statistically significant risks cannot be confirmed [i.e., approximately 100 mSv (protracted doses) or 50 mSv (acute doses)], the shape of the appropriate dose-response curve is not known, because the signal-to-noise ratio of epidemiological data or laboratory data becomes too small. All the dose-response relationships shown in Figure A.1 are possible descriptors of low-dose radiation oncogenesis, and different endpoints (e.g., carcinoma versus sarcoma induction, breast-cancer versus lung-cancer induction) may well show qualitatively different dose-response relationships. At the low and intermediate doses (0.2 to 1 Sv) that are generally amenable to investigation, there is a large amount of data, both from epidemiological studies and from laboratory studies, that is consistent with a linear dose-response relationship. It is important to bear in mind that certain subgroups [e.g., children, the developing embryo or fetus, and genetically susceptible individuals, such as individuals who are heterozygous for the ataxia telangiectasia gene (ICRP, 1998)] will exhibit higher risks, while other subgroups, such as elderly individuals, will exhibit lower risks.

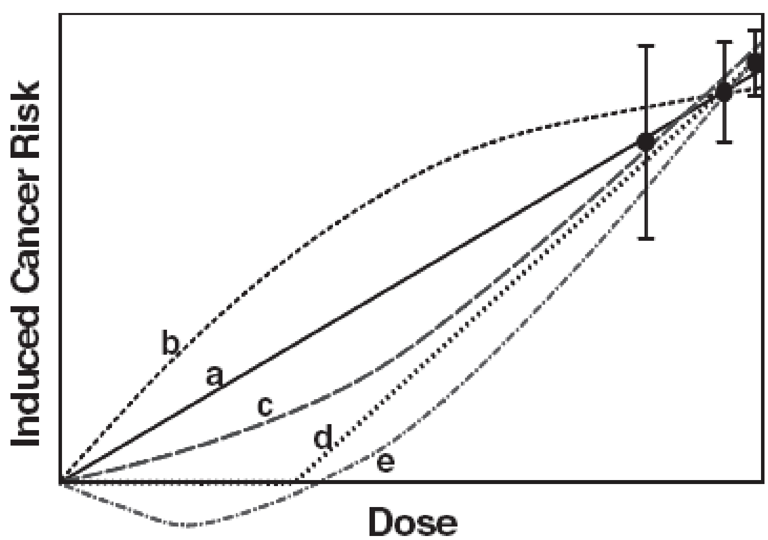

Fig. A.1. Possible dose-response relationships for low-dose radiation oncogenesis: (a) linear, without threshold; (b) downwardly curving: larger risks at low doses than predicted from higher doses; (c) upwardly curving: lower risks at low doses than predicted from higher doses; (d) threshold: zero risk at low doses, risk increases at higher doses; and (e) hormetic: benefit at low doses, risk increases at higher doses (NCRP, 2003b).

Appendix B

Risk Associated with Doses Higher Than the Limit

NCRP's dose limit recommendation of 5 mSv per event for ADT systems is the same as the recommendation for members of the public for infrequent exposures. However, NCRP recognizes that unintended overexposures could occur by accident, particularly considering the inability to control access to the radiation control zone between the ADT system and the targeted object and the likely inability to provide advanced warning to members of the public that might be exposed. Such doses may not necessarily represent significant increases in risk, as long as they are not frequently repeated. Table B.1 lists possible health risks associated with a single exposure resulting in an effective dose ≥5 mSv.

For effective doses up to and including 50 mSv, the primary health effect is an increased lifetime risk of fatal cancer, and the risk level is directly proportional to dose, assuming the linear-nonthreshold model [see NA/NRC (2006) for an explanation of various low-dose extrapolation models used in radiation risk assessment]. Thus, a 50 mSv effective dose would result in an assumed 10-fold increase in cancer risk (i.e., 0.25 % increased risk) over that assumed for a 5 mSv effective dose (i.e., 0.025 % increased risk). This low percentage of radiation-related risk adds little to the relatively high baseline lifetime fatal cancer risk of about 21 % (Horner et al., 2009). Non-stochastic health effects in the exposed embryo or fetus typically begin at doses between 100 and 250 mSv, depending on the stage of gestation (Table B.1). The risks largely include developmental defects, particularly of the neurological system. These data reflect the risk for a population and do not indicate the risk of any particular exposed individual for whom the risk could be greater or smaller.

TABLE B.1—*Health risks associated with various levels of effective dose.*

Effective Dose (mSv)	Excess Lifetime Risk of Fatal Cancer (percent)[a]	Risk of Birth Defect or Spontaneous Abortion for Exposed Embryo or Fetus[b]	Risk of Deterministic Effects[c]	Examples of Individuals Who Might Receive this Level of Effective Dose[d]
5	~0.025	Negligible	Negligible	Members of the public receiving infrequent dose[e]
20	~0.1	Negligible	Negligible	Diagnostic radiology patients receiving a spiral CT whole-body scan
50	~0.25	Negligible	Negligible	Occupationally-exposed individuals receiving annual occupational dose limit[e]
500	~2.5	Risk varies dependent upon stage of gestation[f]	Below, but approaching, the thresholds for most deterministic effects	Individuals receiving limit for a life-saving activity[e]
5,000	~25	~100 %[f]	Exceeds the thresholds for most deterministic effects. Greater than 50 % chance of death within three weeks after exposure, without medical intervention[g]	Cancer patient receiving bone marrow transplantation therapy

[a]Based on a risk of 0.005 % fatal cancer deaths per millisievert (NCRP, 1993) in a population of equal numbers of males and females and all ages. There are large ranges of uncertainty associated with these point estimates, particularly at the lowest doses. Point estimates are shown only as an indication of the magnitude of cancer risk, and must not be considered precise measures of risk. These estimates may be low by a factor of two or more in situations where dose is delivered at a high dose rate.

[b]Radiation-induced birth defects in individuals are primarily neurological with risk varying during gestation. See Table 4.1 of NCRP Commentary No. 9 (NCRP, 1994) for a description of risks for specific health effects at various stages of development of the embryo or fetus.

[c]Deterministic effects are health effects where the severity varies by dose and for which a dose threshold usually exists. Thresholds are generally organ specific and depend upon the fraction of cell death required to compromise organ function.

[d]Listed are examples of individuals who might receive such doses under current radiation protection guidelines or under current state-of-the-art medical practice.

[e]NCRP Report No. 116 (NCRP, 1993).

[f]NCRP Commentary No. 9 (NCRP, 1994).

[g]Death at this dose level would likely be caused by hematopoietic failure. Recovery is possible with antibiotics, transfusions, bone marrow transplantation, or other types of medical intervention.

Appendix C

Safety Design Features

Equipment standards should be designed to meet national or international standards for safety such as those of Underwriter's Laboratory Inc., National Electrical Manufacturing Association or the International Electrotechnical Commission. In addition, a Radiation Safety System, consisting of passive, active and administrative subsystems, should be in place to protect against prompt radiation fields from operation of accelerators deployed in ADT. Such a system is made up of the Radiation Control System (RCS), a system that keeps radiation away from personnel, and the Access Control System (ACS), a system that keeps personnel away from prompt radiation hazards.

C.1 Radiation Control System

The RCS generally consists of a passive element (i.e., shielding) and an active system, such as electronic protection devices with sensors ensuring that the beam is contained within a safe and approved envelope of beam parameters. Conditions that could result in an excessive level of radiation in the occupied areas are also detected and terminated by the active safety system (Casey et al., 1988; Liu et al., 2001; Rokni, et al., 2009).

C.1.1 Shielding

Personnel protection against prompt radiation fields in accelerators is primarily achieved by attenuation of radiation with sufficient thickness and use of appropriate shield materials (high Z material for attenuation of photons and hydrogenous materials for attenuation of neutrons). Shielding can either be placed locally on, or near, accelerator components or constitute a housing enclosure. The degree to which the radiation level must be attenuated depends on several factors, such as: (1) the radiation source terms, (2) the distance from the radiation source to the dose point of interest, (3) estimate of the time that the workers or public may spend at the dose point, and (4) the required dose limits outside the shield (Rokni et al., 2007).

Various modes of accelerator operation (e.g., normal beam losses and abnormal beam losses under credible scenarios), as well as appropriate dose limits for different scenarios, need to be considered in the shield design process. In general, normal beam losses occur at specific locations, such as beam stop or beam dump, collimators, or other beam-defining apertures, bending magnets, while abnormal beam losses could be assumed to occur at any point, except for locations that can be specifically excluded by design. The normal beam loss points can then be locally shielded and the rest of the machine, where routine beam losses are not planned, can be less shielded.

C.1.2 Active Radiation Control System

Considerations of cost and/or space could prohibit use of shielding against the full capability of an accelerator or full beam losses at all locations. An active system can offer a cost-effective solution to meet both the safety and operational requirements in an accelerator facility. Components of such a system typically consist of beam power-limiting devices and active radiation monitors.

The active RCS includes a radiation detector or system of detectors typically placed in occupied areas. These detectors should monitor the radiation levels and be interlocked to take actions that may range from providing warning signals to turning off the accelerator if a preset trip level is exceeded (for example, 0.1 mSv h^{-1} in occupied areas). The active components of the RCS should be designed to be fail-safe and interlocked to terminate the beam if the system is not functioning properly.

C.1.3 Radiation Control System: Passive versus Active Systems

In general, the use of shielding is preferred as the use of active systems requires continual efforts to monitor instrumentation performance and reliability. The passive and the active components should be used as complementary systems and limits for reliance on the use of active RCS should be established. In the case of high power, high energy particle accelerators, sufficient shielding should be present to limit the radiation dose rate below an acceptable level in potentially occupied areas. In the case of accident, it is suggested that a prudent level might be set at between 0.01 and 0.1 Sv h^{-1} in areas that could be occupied by radiation workers (Rokni et al., 2009).

C.2 Access Control System: Access Controls, Interlocks, and Emergency Switches

The Access Control System (ACS) is a personnel safety system consisting of electrical interlocks and mechanical barriers and locks, along with the system logic that prevent personnel from entering beam enclosures and other areas in which the potential for high radiation exposure exists so that they are protected against unshielded prompt radiation (ANSI, 2009; Vylet et al., 2009). ACS allows for authorized access to accelerator and beam housing under safe conditions.

The interlocks also serve to shut off the radiation source if any of the interlocked barriers into beam enclosures are breached. The ACS needs to contain redundant subsystems from the sensors through the logic to the hazard power sources. Fail-safe devices and interlock logic circuit designs must be used. Field devices must be capable of handling two independent circuits or consist of dual independent devices at a single location. The hardware components must be capable of maintaining high reliability in the radiation environments in which they operate. The subsystems must be protected from inadvertent tampering or modification. Computers used for ACS interlocks must be dedicated and isolated from external links that can influence the operation of the system. All parts of the ACS must be under strict configuration control. All changes in hardware or software must be thoroughly tested for the intended function and for effects on other parts of the system. In addition to engineered interlock systems there are administrative requirements and procedures covering ACS operation, testing, and modifications (DOE, 2005).

Acronyms

ACS	Access Control System
ADT	Active Detection Technology
ALARA	as low as (is) reasonably achievable
CAARS	Cargo Advanced Automated Radiography System
DTRA	Defense Threat Reduction Agency
PFNA	pulsed fast neutron analysis
RCS	Radiation Control System
SNM	special nuclear materials

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